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Chapter 10

Induced Polarization Effects Associated With Hydrocarbon Accumulations: Minimization and Evaluation of Cultural Influences

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Abstract

The use of induced polarization (IP) methods in oil and gas exploration dates back to the 1930s, but the validity of anomalies has been difficult to establish. Although recent geochemical and downhole research has verified the source of IP anomalies in some geologic environments, the influence of cultural (anthropogenic) features on the electrical data remains a serious stumbling block to the acceptance of electrical methods in oil exploration. Spurious effects from power lines, pipelines, fences, and well casings can be misinterpreted as anomalies from hydrocarbon alteration or can mask true alteration anomalies.

The cultural problem is not insurmountable, however, and it is not valid to assume automatically that all IP anomalies measured over oil fields are the result of culture. A case study of the development of an oil field near Post, Texas, illustrates how proper survey design can be used to minimize and evaluate the effects of culture in the interpretation of IP survey data. Evaluation of before-and-after IP data sets and two-dimensional finite element modeling strongly support the interpretation that the observed IP anomaly results from hydrocarbon-induced alteration and not from well casing or other cultural effects. Furthermore, the interpreted extent of the IP anomaly as defined in 1982 agrees well with the productive limits of the field as it exists more than 12 years later.

INTRODUCTION

In recent years, the sediments above some hydrocarbon reservoirs have been shown to be altered by microseepage from the reservoirs (e.g., Donovan, 1974; Ferguson, 1977; Donovan et al., 1981; Schumacher, this volume). Some of the alterations in the sediments are potential targets for surface-based electrical exploration techniques, since these alterations can result in a change in the ground resistivity in the chargeability (induced polarization or IP), and sometimes in both of these characteristics. Correlation of seepage-induced alteration with electrical anomalies has been established in some environments (Oehler and Sternberg, 1984; Sternberg, 1991). However, many case histories of electrical surveys over known oil fields remain unconvincing when not corroborated by extensive core hole analysis from drill holes both on and off the field. The electrical methods themselves (measurements in various forms of ground resistivity and IP effects) are well-established techniques and have been used in mineral exploration for decades (e.g., Sumner, 1976; Telford et al., 1976). Their use over known oil fields, however, is often compromised by the presence of electrically conductive cultural features such as fences, well casings, power lines, and pipelines.

Our discussion specifically addresses the cultural problem and how it can be minimized and evaluated when using electrical methods in oil and gas exploration. If the cultural problems can be overcome, the use of electrical methods is attractive in several ways. An electrical crew is typically made up of only three or four people and is thus relatively low in cost, low in environmental impact (no drilling or blasting and no large vehicles), and the depth of investigation is variable, thus the target geochemical alterations need not extend to the surface to be detectable.

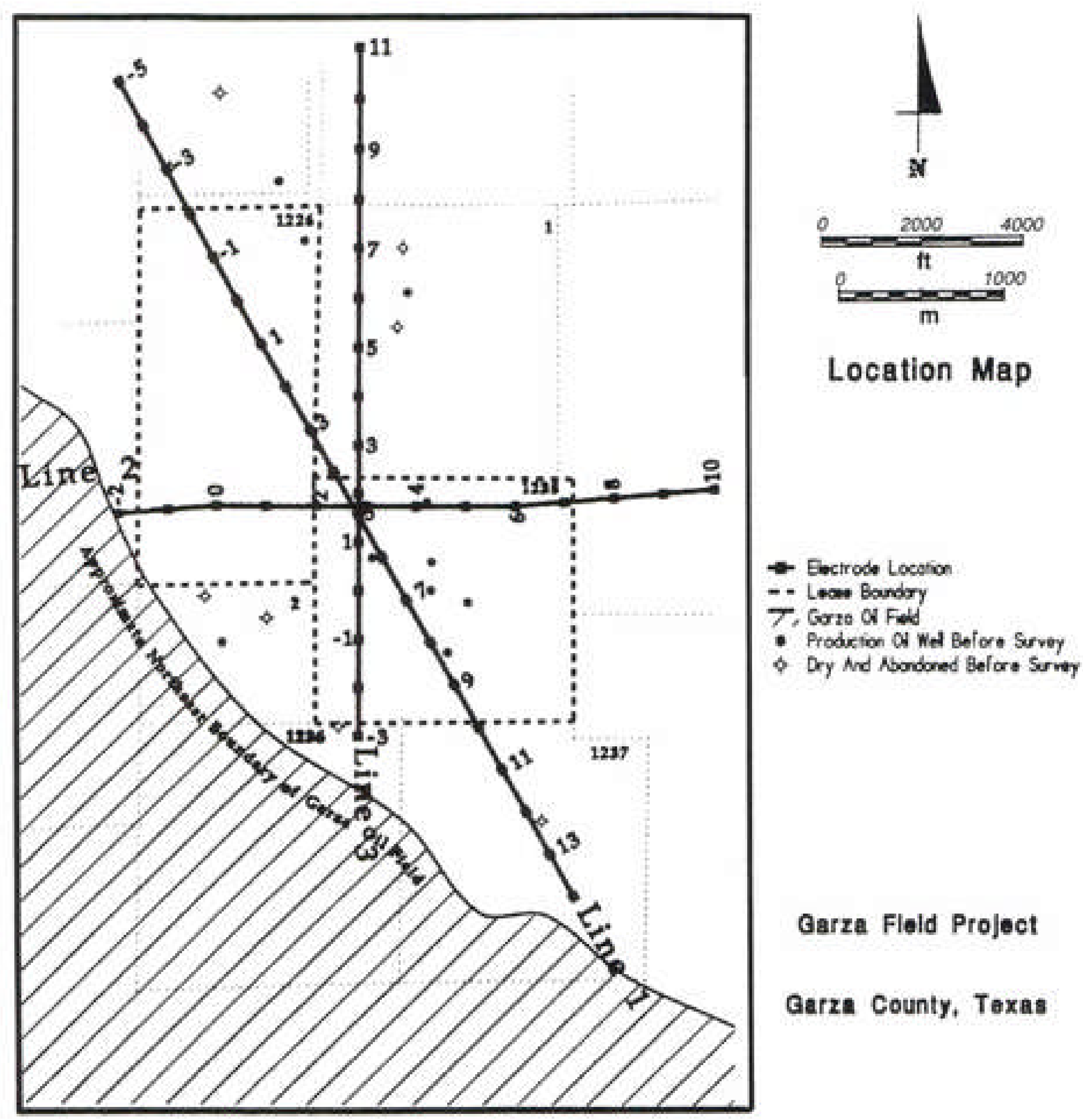

Figure 1 — Location map showing the three original dipole-dipole IP electrical survey lines over the small developing field near Post, Texas (dipole length is 300 m, or 1000 ft).

BACKGROUND AND LOGISTICS

Background

The electrical survey performed in 1982 near Post, Texas, had two specific goals. Six production wells had been recently drilled in Lease Block 1235 (Figure 1), and leases in Block 1226 to the northwest were becoming available. Since oil production was only 10 - 50 bbl oil per day per well in Block 1235, it was important for the operator to minimize the number of dry wells drilled while developing and extending the field. Within strict budget constraints, the goals of this project were:

1. To determine whether production was likely in the leases becoming available in Block 1226 and, if so, how far to the northwest production extended,
2. To determine the approximate extent of the oil field within Block 1235 since the low production rate of each well made minimizing the number of dry wells an important economic concern (a 10-acre well density was permitted).

Production in the Garza field itself (south and west of the lease blocks under study) is from the San Andres and

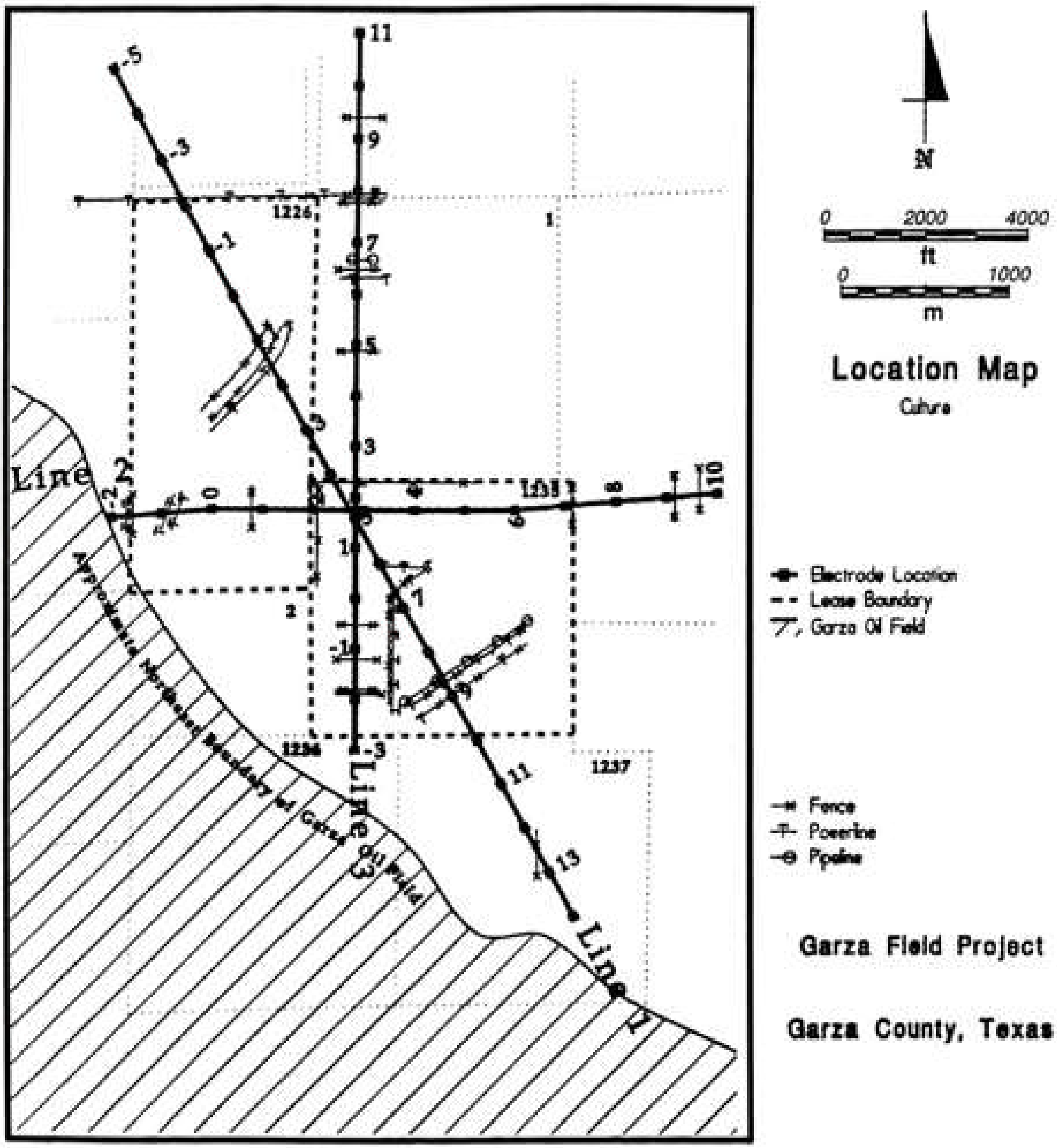

Figure 2 — Culture map showing the location of pipelines, power lines, and fences relative to the three original survey lines (dipole length is 300 m, or 1000 ft).

Glorieta formations of the Lower Permian. The traps result from a loss of porosity on and flanking an anticline, and a permeability pinchout occurs to the east (Hild, 1986). There are several separate, thin producing zones in the lower two-thirds of the San Andres, stacked vertically and offset successively to the southwest. Production in the eastern part of the field is therefore stratigraphically deeper than in the west (Ward et al., 1986). The field produces 36 – 38° API oil from dolomites at depths of 887 - 994 m (2910 - 3260 ft) (Myres, 1977). Although there is no information on percentages of H_2S, most oils produced from the San Andres are described as borderline between sour and sweet. Production in Block 1235 and to the north in Block 1 is assumed to be physically separate from the main Garza field to the west and south on the basis of drilling results. Overlying the San Andres is the upper Guadalupian Yates Formation, composed primarily of sandstone and shale.

The three survey lines that were run intersected in the northwest quarter of Block 1235; the layout of the lines was chosen on the basis of culture and the need to evaluate Block 1226. Figure 2 shows the cultural features present

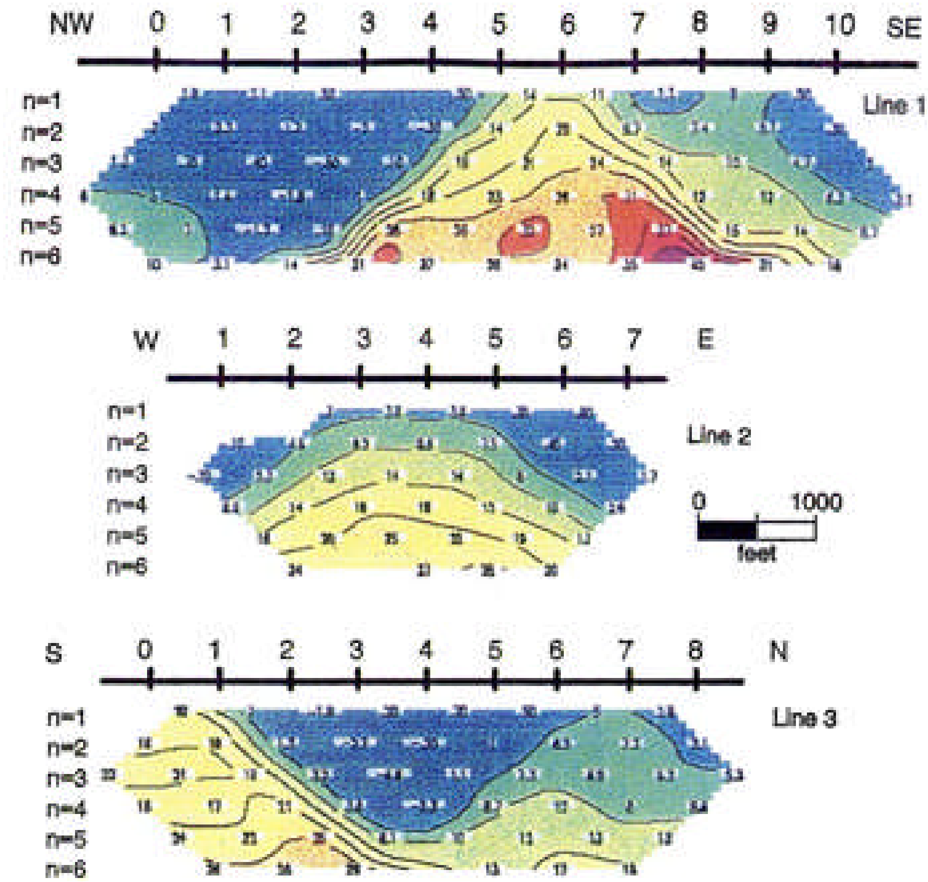

Figure 3 — Induced polarization (IP) data in pseudo-section form for the three survey lines. All values are in milliradians; dipole length on all lines is 300 m (1000 ft)

at the time of the survey. Line 1 extended from past a dry well southeast of production, passed the producing wells, and proceeded northwest across Block 1226. The starting point for line 1 was chosen on the basis of the pipeline and power line combination along a road at about station 8.5. The power line was made up of two three-phase circuits capable of at least 20 kV. The combination of the power line and pipeline was expected to be the strongest cultural influence; thus, the field crew placed the line such that this culture would be in the middle of a dipole rather than close to an electrode position. The power line located along the northern boundary of Block 1226, however, turned out to be the strongest active noise source. Line 2 crossed the production west to east, providing a different orientation to the culture.

Line 3 crossed the production south to north and extended past a separate production field in the northern half of Block 1. The placement of line 3 was chosen to maximize the distance of the line from the two north-south fence sections that can be seen paralleling the line from approximately station 0 to 2 on the west and from station -2 to 0 on the east. Both fences were made of barbed wire strung on mostly wooden posts, with some metal stakes. This placement put the line more than 150 m (500 ft. or one-half the dipole size) from the parallel culture. Budget constraints did not allow additional lines or extensions of the original lines.

Survey Logistics

The data were gathered using the dipole-dipole array, a common array in mineral exploration surveys. A square wave signal at 0.125-Hz was transmitted into a grounded dipole. The resulting magnitude (in millivolts) and phase shift (in milliradians) of the received signal was measured in a similar sized receiver dipole, collinear with the transmitter dipole. The dipoles were each 300 m (1000 ft) long, providing a depth of investigation of about 600 m (2000 ft) when the transmitter and receiver dipoles were six dipole lengths apart (n-spacing = 6). Matched quartz oscillators in the receiver and transmitter controller were synchronized and locked each morning prior to the field work to achieve absolute phase measurements. Data were stacked and averaged in the field until acceptable standard errors were achieved and were then stored on magnetic tape. Each stack consisted of at least 16 cycles, and a minimum of two stacks were made at each position to establish repeatability of the data. If the two stacks differed by 5% or more in resistivity, additional longer stacks were recorded until data blocks were repeatable within 5%. Transmitted currents ranged from 12 to 18 amps, depending on local contact resistance. One channel of the receiver monitored the transmitted wave form via a hard wire link between the transmitter and receiver.

The acquired data include calculated apparent resistivity (in ohm-meters) from the measured received magnitude, measured raw phase shift (in milliradians), and calculated three-point decoupled IP (in milliradians). The IP data (Figure 3) are displayed in standard pseudo-cross-section format, with stations along the top of each plot and increasing n-spacing or separation down the side of the plot, corresponding to increasing depth. Contours are in milliradians, and "warm" colors (red and orange) indicate high IP values, while "cool" colors (green and blue) indicate low IP values in these plots.

It is important to note that the depth of production in this field is substantially below the maximum depth of investigation of the survey. The intent of the survey was not direct detection of the oils but rather detection of alteration of sediments above the oils.

As noted, this discussion is concerned primarily with the IP data since this is the electrical property that showed the largest anomaly associated with the oil field. In the original interpretation and modeling in 1982, all electrical properties were considered.

Preliminary Results

Upon completion of line 1, a definite IP anomaly was evident; at that stage, however, it was not possible to state definitively whether the anomalous values were the result of alteration, culture, a combination of the two, or some unrelated geologic source. Lines 2 and 3 were then run at orientations designed to evaluate cultural influences and verify the correlation between the anomalies and the oil fields (regardless of the cause). All three lines of data showed a clear increase in IP values in the area of the six production wells (Figure 3). This was similar to IP anomalies evident over some other oil and gas fields we have studied, as well as some uncontaminated prospects which eventually proved to be productive. Line 3 also showed a weaker but definite IP anomaly associated with the production in the northern half of Block 1, with near zero background levels between the two production areas. Although the survey had been designed to minimize cultural effects, we felt it was necessary to further evaluate the effects to interpret the data set. As seen in these lines alone, the IP anomalies could be interpreted as the result of the surface culture (power lines, pipelines, well casings, and fences), alteration of sediments above the oil field, or a combination of both.

Note that there are small negative values seen adjacent to the IP anomalies. This is not unusual because a decrease in IP is often seen adjacent to polarizable bodies both in field measurements and in modeling of some horizontally layered environments in which the deepest layer is substantially more conductive than the overlying layers. Negative IP effects are also associated with culture (Sumner, 1976). In this case, background IP values are near zero, and the slight decrease results in small negative values in the pseudo-section.

EVALUATION OF CULTURAL EFFECTS

Position Relative to Electrodes

The effects of grounded surface culture (such as power lines, pipelines, fences, and well casings) on electrical data are strongly dependent on the location of the culture relative to the survey line electrodes. Survey crews plan lines on this basis; spurious effects are greatly minimized when electrodes are placed symmetrically with respect to the culture. For example, if a power line crosses a survey line, the power line should cross in the middle of a dipole rather than near an electrode.

This strong variation in cultural effects with respect to location relative to electrodes is well documented in the literature by field data and in mathematical modeling (e.g., Nelson, 1977). An illustration of this dependence is shown in Figure 4, which shows the computer-generated model response of a small polarizable body placed at the surface midway between electrodes -1 and 0 (Figure 4a) and near electrode 0 (Figure 4b). These results are consistent with field experience. When the polarizable body is placed in the middle of the dipole, the resulting anomaly is weaker and more symmetrical than when the body is near an electrode. Note that in this simple example, the difference between placing the anomalous body midway between electrodes and near an electrode is almost 25 mrad in some parts of the anomaly. The anomaly that results from this surface polarizable body is shaped like an inverted V, called a "pants-leg" effect, which is also consistent with other models and field experience. The strongest IP effect extends diagonally downward in both directions from the source of the anomaly.

The size of the polarizable body used in the model for Figure 4 was 0.1 by 0.2 dipole lengths, which is much larger than normal cultural features such as pipelines and power lines. The size discrepancy is due to the limitations of the two-dimensional finite-element modeling program used to generate this illustration.

We should also note that based on our field experience, the strength of cultural anomalies is also dependent on grounding of the culture and on background resistivity of the ground itself. In high-resistivity environments, cultural effects are stronger than in low-resistivity environments. When culture is poorly grounded or background resistivities are low, we often see very weak or no cultural effects at all. Ground resistivities at this project site were low, ranging from 4 ohm-m in the shallow $n = 1$ data up to 20 ohm-m in the deeper $n = 6$ data.

It is possible to use this dependence of cultural effects on location (relative to electrodes) as a method of evaluating those cultural effects. This is done by repeating the suspect portion of the survey line with electrodes shifted along the line. Anomalous values that result from surface features or culture should show strong changes after shifting the electrode positions, similar to those seen in Figure 4. Deeper, larger features should show relatively little change with the shift in electrodes.

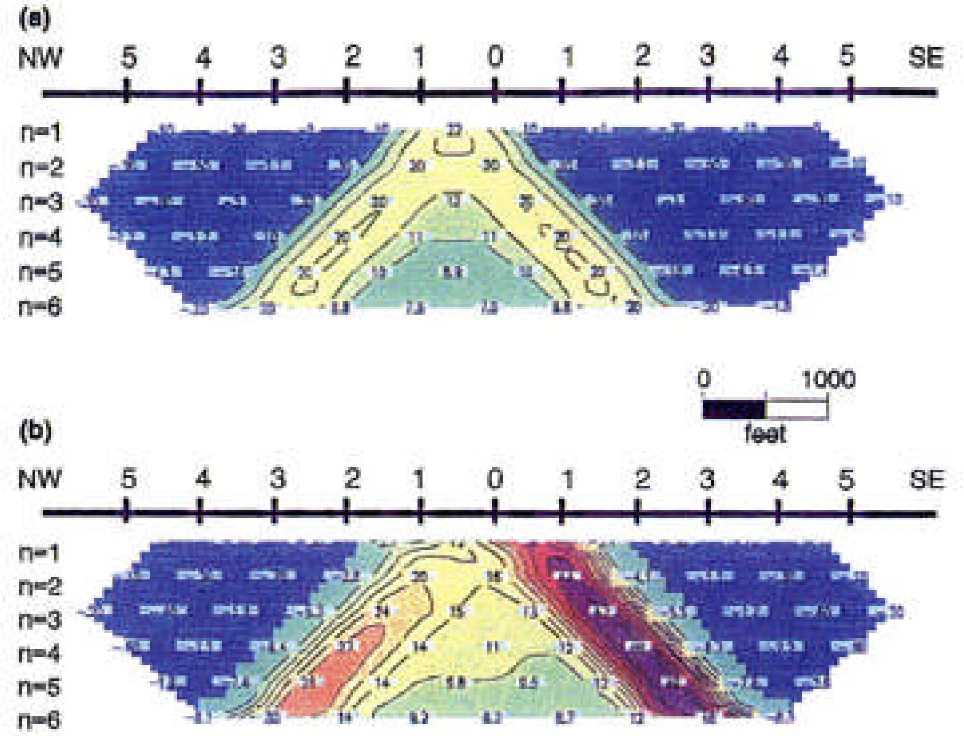

Figure 4 — 2DIP modeling results for (a) a small surface polarizable body located between electrodes -1 and 0 and (b) the same body located at electrode 0. Note the strong difference between the anomaly created by the feature in the center of the dipole versus the anomaly created when the feature is at or near an electrode.

For this project, the portion of line 1 centered approximately at station 6 was repeated since this area shows the strongest IP values and line 1 data are critical in evaluating Lease Block 1226. After completing line 1 with electrodes located at integral station numbers (0, 1, 2, etc.), transmitting and receiving electrodes were then shifted 150 m (500 ft) along line. Thus, electrodes were then located at stations 0.5, 1.5, 2.5, etc. This shift is one-half the dipole size, thus a surface feature equidistant from electrodes in the original layout would be at an electrode in the shifted layout. Surface features causing an anomaly in the original layout should be minimized in the shifted layout, and features causing no anomaly in the original layout should show strong anomalies in the shifted lay out (assuming the features are causing any anomalies at all). In Figure 5, the original IP data (Figure 5a) are compared with the IP data after shifting the electrodes (Figure 5b). Cultural features are plotted across the top of the line for reference.

Both the overall appearance and the strength of the anomaly are similar in the two data sets. The only significant change is along the diagonal of data extending downward to the left from dipole 8.5 - 9.5, where IP values have decreased relative to the original data set. This decrease is interpreted to be a cultural effect from the pipeline and power line combination located approximately at station 8.6. In the original data set, these cultural features were nearly centered between electrodes 8.0 and 9.0 to minimize their effect; after shifting electrodes, the culture is close to the electrode at 8.5, maximizing the cultural effects. In this case, the cultural effect of the pipeline and power line appears to be a negative IP effect, reducing IP values along the affected diagonal.

Also note that a power line is located approximately at station 6.1, which is near the electrode in the original survey but midway between electrodes in the repeat survey. If this power line had caused a substantial portion of the anomaly in the original survey, we would expect a significant change between the two data sets in this area. There is little change in the anomaly after shifting the electrodes, particularly when compared to the change seen in the model results in Figure 4 discussed previously.

The absence of any significant change in either anomaly strength or anomaly appearance (except along the one diagonal extending from the pipeline and power line at station 8.6) strongly suggests that the anomalously high IP values seen in the original data set are not the result of surface or cultural features. The low-resistivity back ground (4 - 20 ohm-m) is probably the primary reason for the apparently weak cultural effects on the data. We frequently encounter pipelines, fences, and power lines that had little or no effect on the data, although in some other environments, these features make data interpretation impossible.

Before-and-After Comparisons

Well casing effects are a possible source of anomalous IP values and must be considered in the interpretation of electrical data over a producing field. While casing effects do not always appear similar to surface culture, they are dependent on location and background resistivity, similar to surface culture. In this project, a total of six well casings were in place when the original three survey lines

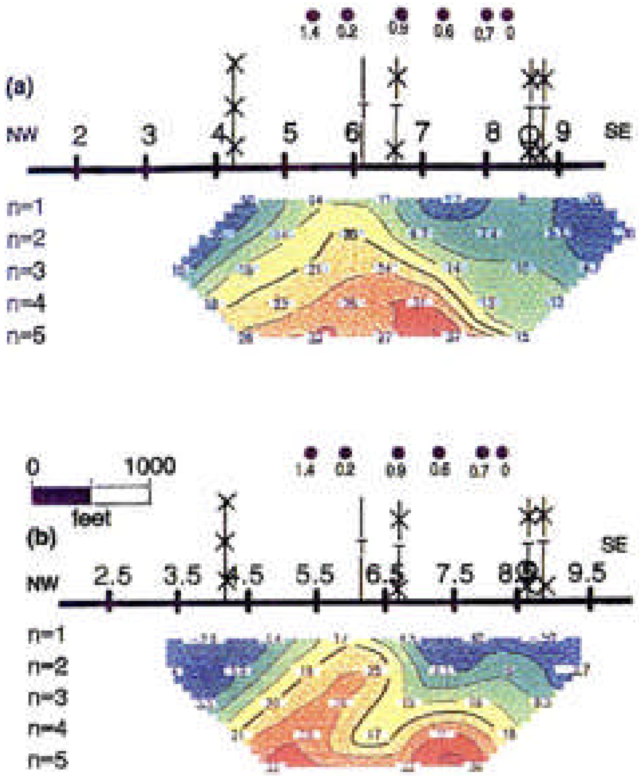

Figure 5 — (a) IP data from the original line 1 measurements versus (b) measurements made after electrodes were shifted 150 m (500 ft) along line. Culture is shown along the top of the pseudo-section, with distances of the well casings off line (in dipole lengths). Note the overall similarity of the two anomalies, except along the diagonal extending downward to the left from the culture near electrode 8.5 in part (b). (See Figure 2 for key to culture symbols.)

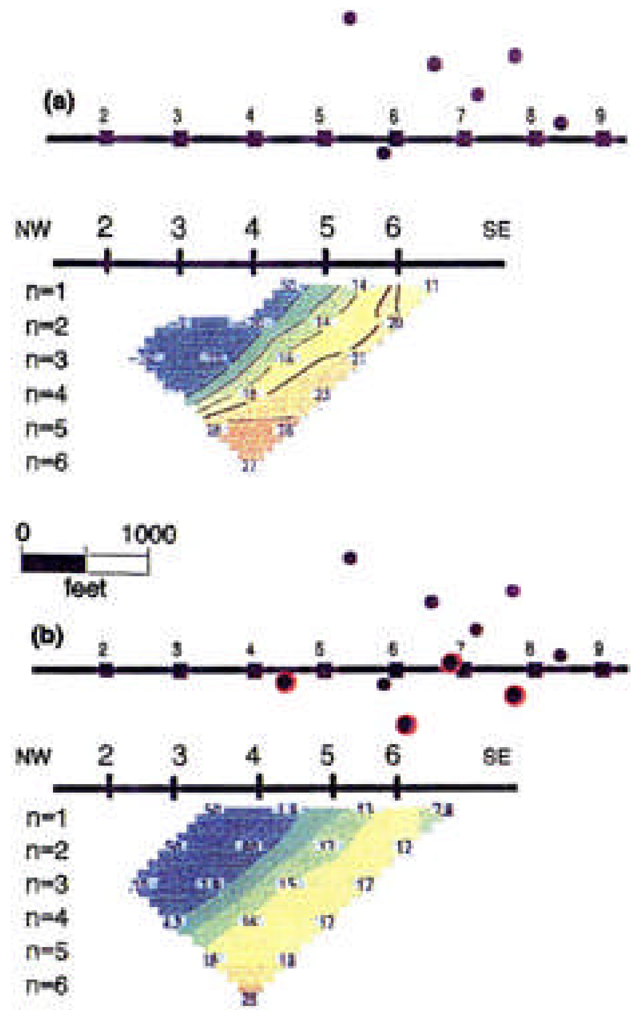

Figure 6 — (a) IP data from the original line 1 measurements versus (b) repeated measurements after four new wells were drilled, cased, and in operation. There is a slight decrease in IP values, but otherwise little effect from the new wells, one of which is close to the electrode at station 7.

were acquired. Shortly after the survey lines were completed, four additional wells were drilled and casing was set. By returning to the site and repeating a portion of line 1 after the new wells were in place, a before-and-after comparison could be made on the effects of the four new wells.

Figure 6a shows part of the original IP data from line 1 with a plan view diagram of the oil wells relative to the electrodes. Figure 6b shows the part of line 1 that was repeated and a plan view with the location of the new wells added. This repeat of the line 1 data was done after the new oil wells had been producing for about 30 days, allowing the casings, cement, and pipelines to "settle" electrically.

The addition of the four new well casings had little effect on the data, suggesting that well casings are not a strong contributor to the IP anomaly in this environment. Based on proximity to the line, and to electrodes, we might expect that the new well casings would have an even stronger, effect on the data than the original casings, but the shape of the anomaly is unchanged, and only one diagonal of data appears to be altered slightly by the new casings. In particular, note the new well casing on line and close to the electrode at station 7 and that two of the remaining three new wells are within 0.3 dipole lengths of the line. If well casings were affecting the data, these new casings should have been obvious in the data when the line was repeated. On the basis of this comparison, well casings are interpreted as having minimal effects on the data. Also, if the casings were affecting the data, it could be a negative IP effect, reducing the IP values, similar to the effect seen from the pipeline and power line combination discussed earlier.

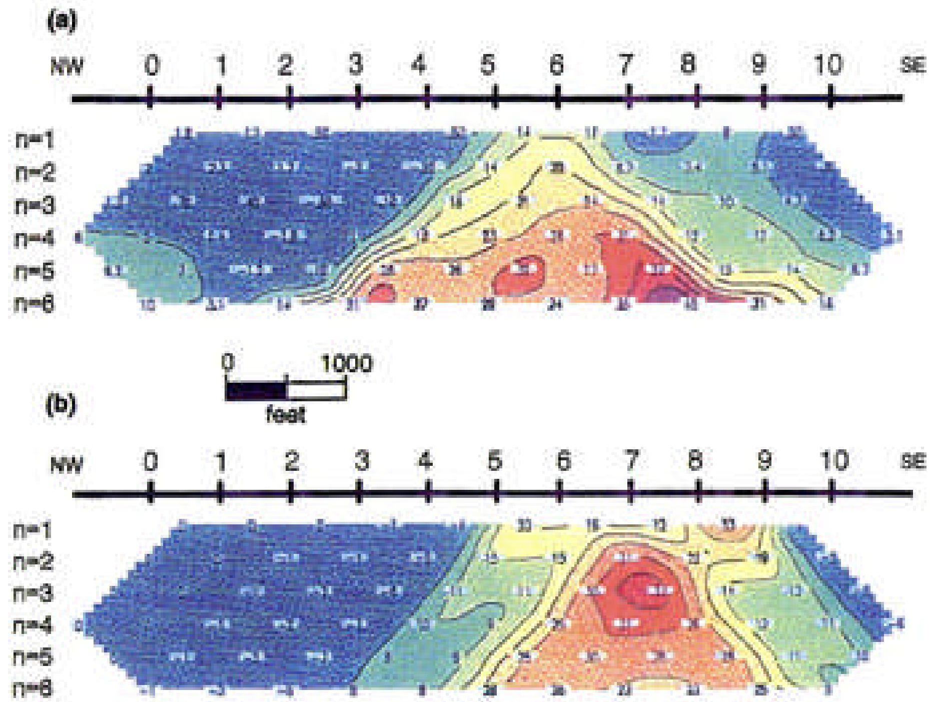

Figure 7 — (a) IP data from the original line 1 measurements versus (b) IP results from the modeling program PIPE, with the complex impedance of the casings varied to force a best fit to the field data.

In addition to the comparison of field data gathered before and after wells were drilled, the effect of well casings was also evaluated using a mathematical program called PIPE written by Holladay and West (1984). The program models the effects of multiple well casings given information about the casing location, inner and outer diameters, longitudinal conductance, wave number, complex impedance, and background resistivity. Using the locations and casing diameters of the six wells in place at the time of the survey, plus conductance figures obtained from U.S. Steel, we varied the complex impedance in an attempt to achieve the best possible fit between the well casing model and the field data.

Figure 7a shows the IP data from line 1, and Figure 7b shows the closest fit obtained using the PIPE program. The strength of the PIPE anomaly is similar to the field data anomaly, although the PIPE anomaly is offset to the south and is shallower than the field data anomaly. The agreement between the field data and the PIPE results, however, could be considered a moderately good fit since it produces an anomaly of about the correct magnitude (although slightly offset from the field anomaly). Local variations in background (not taken into account in the program) and variations in contact impedance along the length of the casing could account for some of the discrepancy.

The four new wells discussed previously were then added to the input model, using the same casing characteristics that had provided the best fit in the model of the original wells. This provided a before-and-after comparison of the casing model effects. If the original results of the PIPE program (including the six original wells) are accepted as a good fit to the field data, then the PIPE pro gram should predict little or no change in the data with the inclusion of the four new wells, since the repeat of line 1 field data after the four new wells showed little change.

Figure 8a shows the well casing model results for the original six wells, and Figure 8b shows the PIPE results for the original wells plus the four new wells (using the physical parameters that had provided the best fit to the original data). The data shown are for the segment of line I that was repeated in the field for comparison purposes.

The well casing model predicts a large change in IP values as a result of the new well casings, contrary to the field results. This suggests that even though a well casing model can be generated that fits the data moderately well, the IP anomaly observed in the field data is probably not the result of well casings. Based on the results of the before-and-after data sets, well casings are responsible for the anomaly only if the casing effects are very selective, that is, the original six well casings are different electrically from the four new well casings. This is considered unlikely because the geology is layered and relatively uniform, the casing sizes and materials are the same, and the new wells were allowed to settle 30 days before the field measurements were made.

ALTERATION MODELING

To verify that a deep, broad polarizable region similar to the alteration detected over some fields (Oehler and Stemberg, 1984) could be the cause of the IP anomaly measured at this site, an in-house 2-D finite-element mathematical program called 2DIP was used to model an oil field alteration anomaly. In this model, the polarizable area is broad, about 5 dipole lengths across (~1500 m, or5000 ft), to represent an area of altered sediments above

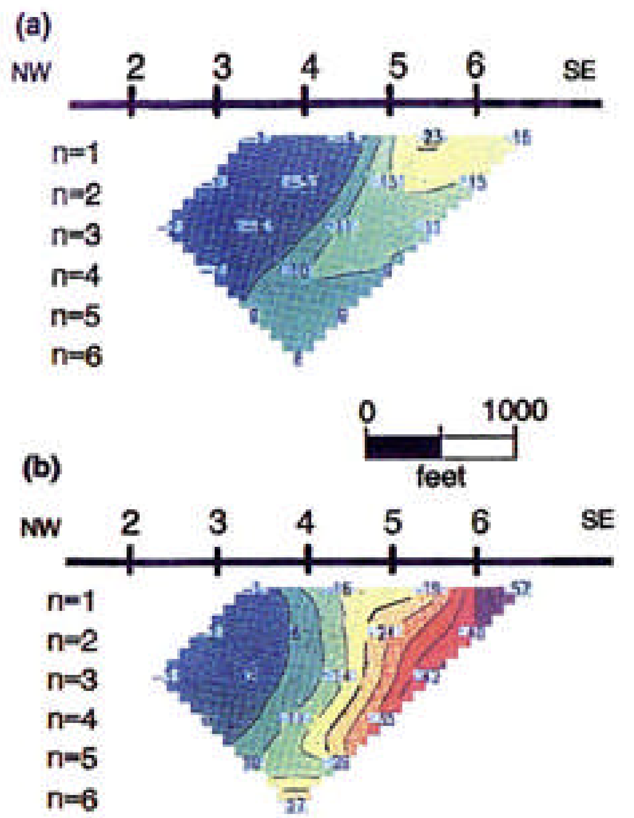

Figure 8 — (a) IP data from the modeling program PIPE for the original six well casings versus (b) PIPE results after adding the four new well casings. Note the strong increase in the IP anomaly as compared to the actual field results shown in Figure 6.

the oil field. The top of this polarizable region is ~230 m (750 ft) beneath the surface. In this model, the polarizable region is relatively simple, with a higher IP response (80 mrad) assigned to the central ~1000 m (3000 ft), and a moderate IP response (20 mrad) assigned to the outer region. Background response is 0 mrad, and resistivities are represented by a layered 4 ohm-m overlying 10 ohm-m. More complex models are possible and may provide a better fit to the field data.

Figure 9a shows the IP field data for comparison with the 2-D model results (Figure 9b). The fit with the field data is moderately good and can be considered as good or better than the well casing model results. The model results produce weak negative values adjacent to the main anomaly. If a more complex model incorporating small localized variations were used, or if weak cultural effects could be added (as suggested here by the comparisons), a good fit with the field data could be generated. Of importance here is not that the model could be fine-tuned to a close fit, but that a broad, moderately deep polarizable region, about the size of the oil field, could generate the IP anomaly observed over this producing oil field.

FINAL INTERPRETATION

The final interpretation in 1982 of the original data set, the shifted-dipole test, and the before-and-after comparisons was that two areas appeared to exhibit electrical anomalies associated with the oil field at depth. These two areas are outlined in Figure 10, comprising the majority of Block 1235 and the northwestern quarter of Block 1. The interpretation of an alteration anomaly rather than a surface culture or well casing anomaly is based on

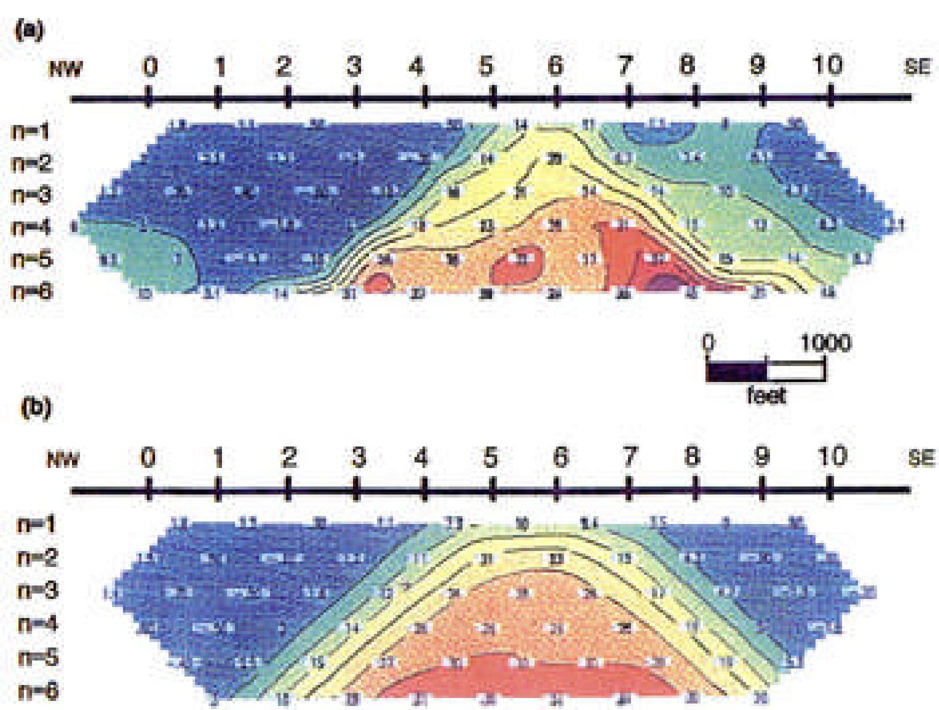

Figure 9 — (a) IP data from the original line 1 measurements versus (b) IP results from the modeling program 2DIP simulating a seepage-induced polarizable region buried at ~230 m (750 ft), based on the interpreted size of the alteration anomaly.

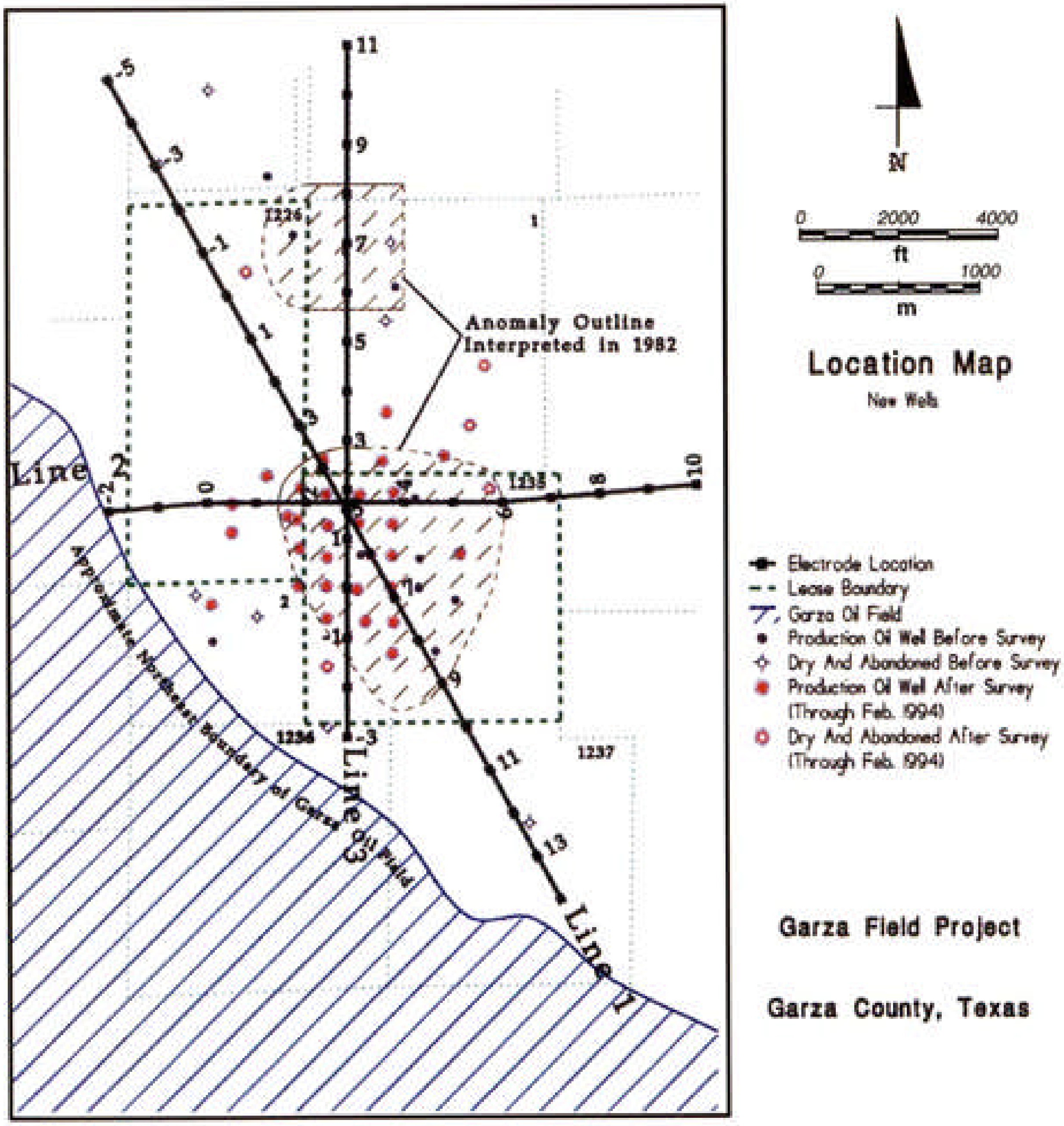

Figure 10 — Location map showing the three survey lines and the outline of the alteration anomaly interpreted in 1982. Also shown are the new wells (producing and dry) drilled since the survey was completed.

the following key elements:

1. The similarity in strength and appearance of the anomaly on all three lines, despite the different orientation and location of dipoles with respect to the culture. In the field data, the anomaly at the intersection of the lines is similar despite the difference in orientation of the receiver dipoles at the intersection and the completely different position of the associated transmitter dipoles (and therefore different cultural influences).
2. The similarity in strength and appearance of the anomaly before and after shifting electrodes on line 1 along line 500 ft. As discussed, this should have produced a significant change in any surface culture anomalies.
3. The similarity in strength and appearance of the line 1 segment after four new wells were drilled. As discussed, if well casing effects were significant, these new wells should have had a major effect on the repeated data.

As noted earlier, interpretation was also based on resistivity data and modeling and on prior experience over producing oil and gas fields.

There are no strong anomalies interpreted in Block 1226. The main alteration anomaly in Block 1235 does not appear to extend to the northwest into Block 1226, nor does the production in the northern half of Block 1 appear to extend very far to the west into Block 1226. In addition, because known production correlated well with the anomalies, there was no indication of lateral migration of the anomaly mechanism, and no lateral offset between the anomalies and production was suspected. On the basis of these interpretations, leases in Block 1226 were not acquired and development of the field in Block 1235 continued.

RESULTS OF THE SURVEY

Figure 10 shows the locations of all wells drilled through February 1994 and appears to confirm the 1982 interpretation of the data. Note in particular the dry well that was drilled (by a different operator) after the survey near station 0 of line 1 in Block 1226. It provides at least partial confirmation that the field in Block 1 does not extend to the west and that the main field in Block 1235 does not extend very far to the northwest. Dry wells near station 6 of line 2 and station -1.5 of line 3 seem to agree well with the interpreted boundary of the alteration anomaly. To date, a total of 23 production wells have been drilled within the outline of the interpreted anomaly, confirming the size of the production area (relative to the small size of the production area in the northern half of Block 1, for example). The excellent agreement between the alteration anomaly outline and the production limits, however, is at least in part a “lucky” interpretation because the lateral resolution of the electrical survey (using this particular dipole size) is probably no better than 150 m (500 ft). Thus, the outline of the actual alteration anomaly could be slightly smaller or larger. It is also important to note that the outline of the alteration anomaly does not necessarily define the exact limits of economic production.

Despite the presence of cultural influences, the final results of this project were of well-defined economic benefit to the operator. Budget money was not spent on leasing the northern half of Block 1226 (which so far has proven to be a relatively unproductive area), and only two dry wells were drilled in developing Block 1235. Had the budget existed, additional work could have added to the interpretation. Additional lines or data gathered with different arrays could have improved the lateral resolution, and shallow core holes could have verified the physical source of the electrical anomalies. Additional deep drilling would certainly be interesting and useful in verifying the correlation between the electrical anomalies and the outlines of production. The survey more than fulfilled its economic purpose, however, and serves as an excellent example of an effective evaluation of cultural effects on electrical geophysical data over a developing oil field.

Acknowledgments — We are grateful to the management of Matthews Oil Company of Lubbock, Texas, for permission to publish this data set with background information. Much of the data and discussion included in this paper appeared previously in Zonge Engineering’s 1983 speculative “groupshoot” project called “Case histories of an electromagnetic method for petroleum exploration” authored by Larry Hughes of Environmental and Safety Engineering (EnSafe) of Memphis, Tennessee, whose efforts and contributions cannot be overstated.

REFERENCES CITED

Donovan, T. J., 1974, Petroleum microseepage at Cement, Oklahoma - evidence and mechanism: AAPG Bulletin, v. 58, p. 429 - 446.

Donovan, T. J., A. A. Roberts, and M. C. Dalziel, 1981, Epigenetic zoning in surface and near-surface rocks resulting from seepage-induced redox gradients, Velma oil field, Oklahoma (abs.): AAPG Bulletin, v. 65, p. 919.

Ferguson, J. D., 1977, The subsurface alteration and mineralization of Permian red beds overlying several oil fields in southern Oklahoma: Master’s thesis, Oklahoma State University Stillwater, Oklahoma, 95 p.

Hild, G. P., 1986, The relationship of San Andres facies to the distribution of porosity and permeability - Garza field, Garza County, Texas, in Hydrocarbon reservoir studies, San Andres/Grayburg formations, Permian Basin: Permian Basin Society—SEPM Publication No. 86-26, p. 429 - 446.

Holladay, J. S., and C. F West, 1984, Effect of well casing on surface electrical surveys: Geophysics, v. 49, p. 177 - 188.

Myres, S. D., 1977, The Permian Basin, era of advancement: El Paso, Texas, Permian Press, 266 p.

Nelson, P. H., 1977, Induced polarization effects from grounded structures: Geophysics, v. 42, p. 1241—1253.

Oehler, D. Z., and B. K. Sternberg, 1984, Seepage-induced anomalies, “false” anomalies, and implications for electrical prospecting: AAPG Bulletin, v. 68, p. 1121 - 1145.

Sternberg, B. K., 1991, A review of some experience with the induced-polarization / resistivity method for hydrocarbon surveys: success and limitations: Geophysics, v. 56, p. 1522 - 1532.

Sumner, J. S., 1976, Principles of induced polarization for geo physical exploration: New York, Elsevier, 277 p.

Telford, W. M., L. P. Geldart, R. E. Sheriff, and D. A. Keys, 1976, Applied geophysics: New York, Cambridge University Press, 860 p.

Ward, R. F., C. C. St. C. Kendall, and P. M. Harris, 1986, Upper Permian (Guadalupian) facies and their association with hydrocarbons — Permian Basin, West Texas and New Mexico: AAPG Bulletin, v. 70, p. 239 - 262.